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MAGNETIZATION SWITCHING IN A MAGNETO-
OPTIC THIN FILM

James M. White, et al

IBM Thomas J. Watson Research Center

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MAGNETIZATION SWITCHING IN A MAGNETO-OPTIC THIN FILM

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by

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13. ABSTRACT <p>An improved technique for observing sub-nanosecond magnetization changes in thin films has been used to study the underdamped oscillatory behavior in a $(Y_{2.5}Gd_{5})Fe_4Ga_{12}$ sample. The measurement set-up uses a version of the alternate sampling technique in which the sensitivity has been upgraded by the use of a lock-in amplifier. By using a shorted strip-line of appropriate length to apply to the film two properly timed magnetic field steps, the precession of the magnetization can be quelled, and the magnetization can be switched between initial and final directions in a half-cycle of the resonant frequency.</p>		

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1. INTRODUCTION

The properties of ferrimagnetic garnet films are of interest for applications including magnetic bubble memories and thin-film magneto-optic modulators. The initial purpose of this particular investigation was to observe the behavior of the magnetization in a $(Y_{2.5}Gd_{.5})(Fe_4O_{11})O_{12}$ film on a gadolinium gallium garnet substrate when an external switching field was applied. In order to detect the magnetization flux change in the presence of the applied switching field, we have used an improved version of the alternate sampling technique¹. The increased sensitivity achieved through the use of a lock-in amplifier made possible the observation of an underdamped oscillatory change in the transverse (rotational) component of the magnetization in the garnet film. Other authors have made related observations in films such as permalloy².

For our experiments, the sample was located in a shorted strip-line by which the switching field was applied. In addition to observing the free oscillations, we have demonstrated how a properly timed field reflected from the short can be used to quell the underdamped precession. This scheme allows the magnetization to be switched between certain initial and final directions in a half cycle of the precession resonance frequency.

Technique for Measurement of Precession Frequency and Damping

When a small external switching field is applied to a uniform domain of magnetic film, the initial magnetization realignment is through a damped precession. The exact behavior of the magnetization in thin

crystalline ferrimagnetic films is complicated by effective internal anisotropy and demagnetizing fields which determine the equilibrium position of \vec{M} and cause the precession to flatten into an elliptical pattern for small switching angles.³ In the multidomain case or in the presence of exchange resonance modes, multiple response frequencies may occur.⁴ A general expression⁵ for the undamped precession frequency of a single ferromagnetic mode in terms of the curvature of the energy surface indicates that the oscillation frequency need not smoothly increase with applied magnetic bias but that significant transitions in oscillation frequency can occur when the applied field shifts the equilibrium or minimum energy orientation. The purpose of our first experiment was to observe the oscillatory characteristics of the magnetization \vec{M} in the sample for various applied fields. A strip transmission line was used to apply a fast rise-time (0.5 nanosecond) change in the external field (Fig. 1). A pickup loop around the sample detected the flux change due to the resultant precession of the magnetization¹.

For the initial measurements, a shorted transmission line with a length much less than uhf wavelengths was used to pulse the sample. The input step pulse, when reflected from the short, created a doubled H field as seen by the sample. The line was made of 1/4" wide brass strips separated by a 1/16" dielectric. With an air dielectric, the characteristic impedance is 70 ohms; with a TFE (Teflon) dielectric, the impedance is 50 ohms⁶. A good match to the input line prevented ringing. The pickup wire, located inside the strip line, was connected

to the differential (A-B) inputs of a sampling oscilloscope through balanced coaxial cables.

Orthogonal sets of Helmholtz coils were used to apply DC and/or 60 Hz AC external fields to the sample. One pair of coils applied a magnetic field in the direction lengthwise to the transmission line. The other pair of coils applied a field transverse to the transmission line and in the plane of the magnetic sample.

At each extreme of the 60 Hz field, a 0.5 nsec rise-time current step was applied to the transmission line. The response in the loop to each input step was a relatively large direct pickup plus a signal due to the magnetization change. The direct pickup did not change from pulse to pulse; however, the contribution from the magnetization response was different for alternate pulses because of the presence of the external 60 Hz field. The oscilloscope took one sample per pulse; therefore, there was a 60 Hz square wave component in the output of the sampling scope amplifiers. The magnitude of this 60 Hz modulation was equal to the difference in the alternate responses, which the oscilloscope scanned at a slow rate. For maximum sensitivity in the presence of the large direct pickup in the loop and of jitter in the timing circuitry, a lock-in amplifier was used to extract the amplitude of the 60 Hz modulation signal. This amplitude was then recorded versus the horizontal scan ramp of the sampling oscilloscope.

It should be noted that the X-Y recorder traces which resulted are the difference in the rate of flux change of the precessing

magnetization in the presence of the two different external bias states. This is perhaps clarified by Fig. 2. In this example, a DC external magnetic field H_{DC} is applied along the length of the transmission line by one pair of Helmholtz coils. The transverse coils apply a 60 Hz AC field with extremes of $+H_{AC}$ and $-H_{AC}$. The step field ΔH is applied each time one of these two extremes is reached. Thus the two initial conditions are $\vec{H}_1 = \vec{H}_{DC} - \vec{H}_{AC}$ and $\vec{H}_2 = \vec{H}_{DC} + \vec{H}_{AC}$. Note that $|H_1| = |H_2|$ in this example. For simplicity, let us assume in the steady state case that the magnetization \vec{M} is parallel to \vec{H} and that internal fields may be neglected.

When \vec{H}_1 is suddenly changed to $\vec{H}_1 + \Delta\vec{H}$, the component of \vec{M} normal to the plane of the pickup loop starts to increase; i.e., the flux through the loop initially increases. However, if $\Delta\vec{H}$ is added during the positive peak of the AC field; i.e., \vec{H}_2 is changed to $\vec{H}_2 + \Delta\vec{H}$, then the flux through the loop will initially decrease. For small $\Delta\vec{H}$, $|H_1 + \Delta H| \approx |H_2 + \Delta H|$, and the precession frequencies should be nearly identical. One response initially increases and the other initially decreases; therefore, when the signals are subtracted through the sampling scope and lock-in amplifier, the two responses will add constructively.

Internal fields or other alignments of the external fields can cause $|H_1 + \Delta H|$ to be markedly different from $|H_2 + \Delta H|$. If the two precession frequencies are unequal, then beating may be observed because our technique only permits one to see the difference between the two signals. The author of reference 3 suggested that by

alternating between a sufficiently large external field and a smaller field, one of the response signals could be assumed to disappear. Our results support this assumption.

Some typical X-Y recorder traces are shown in Figs. 3-5. For the traces in Fig. 3, the external fields were as shown in Fig. 2 with $H_{DC} = 30$ Oe and $H_{AC} = 5$ Oe. ΔH was on the order of 0.3 Oe. A beating or non-exponential decaying phenomenon is apparent in two of these traces. In Fig. 4, H_{DC} , H_{AC} , and ΔH were aligned in the same direction parallel to the plane of the pickup loop. With $|H_{DC}| = 15$ Oe and $|H_{AC}| = 35$ Oe, $|H_{DC} + H_{AC}| = 50$ Oe and $|H_{DC} - H_{AC}| = 20$ Oe. The easy axis, as determined by hysteresis measurements in the plane of the film,⁷ was perpendicular to the pickup loop and applied fields. In Fig. 5, the Helmholtz coils were turned 45° with respect to the transmission line and the currents were adjusted so that $\vec{H}_{DC} + \vec{H}_{AC}$ was 40 Oe parallel to the line and $\vec{H}_{DC} - \vec{H}_{AC}$ was 40 Oe perpendicular to the line. The sample was also rotated so that the easy axis was 45° degrees with respect to the strip line.

The period of oscillation was measured at various levels of external field for orientations along the easy axis, perpendicular to the easy axis, and at a 45° angle with respect to the easy axis. The frequency was calculated by counting the number of cycles per unit time as shown on X-Y recorder plots. Some error is introduced in this pulsed type of measurement since the response waveform is not exactly sinusoidal. However, maximum spread of 40 MHz occurred in different measurements

of the same sample for a given field level and film orientation. Fig. 6 is a plot of frequency versus $|H|$ for the three orientations mentioned. With fields of a few oersteds applied approximately perpendicular or parallel to the easy axis, the observed frequency is fixed at about 460 MHz. Above a certain level of the field, which is dependent on the axis orientation, the frequency drops to a lower value. Above this, the frequency increases monotonically. For the 45° orientation, the frequency increased from the low field value without an observed transition. The transition at low fields seems to coincide with the observed disappearance of domains which may be observed due to Faraday rotation of light passing up through the film.⁷ No domains were seen with the bias field in the 45° orientation. The two lower curves of Fig. 6 may be compared to Fig. 1 of Ref. 5 which shows a similar behavior as the bias field increases and the equilibrium direction of the magnetization changes from a direction normal to the applied field to a direction in line with the applied field.

The damping rate was observed to vary with field level. The $1/e$ point occurred in as few as one and a half cycles at lower fields, but the precession persisted for tens of cycles at higher fields. This trend has been documented in permalloy film, and various explanations have been given.²

Two-Step Technique to Quell Precession

For many applications including magneto-optical modulation, it is desirable to have the magnetization change from one direction or "state" to a final direction or "state." However, in an underdamped film such

as we have described, it takes many periods for the magnetization to settle into the switched direction after only one step pulse is applied.

Because the damping coefficient is small, we have been able to switch and stop the magnetization using a two-step pulse. The intuitive reasoning behind this method is illustrated by the simple model of Fig. 7.

Assume that before $t = t_0$, \vec{M} is at rest along \vec{H}_0 . At $t = t_0$, the field is stepped by an amount $\Delta\vec{H}$. At $t = t_1$, corresponding to a half-cycle of the precession frequency, \vec{M} will be aligned along $\vec{H}_0 + 2\Delta\vec{H}$, if we neglect damping and assume a symmetrical elliptical behavior. If, at $t = t_1$, a second step $\Delta\vec{H}$ is added to the external field, we have the condition where \vec{M} and the external field are aligned again, and the precession is quelled.

The two step field incrementation can be easily implemented by lengthening the transmission line used in the earlier experiment. The initial input step creates the $\Delta\vec{H}$ at $t = t_0$. With the short positioned a quarter wavelength from the magnetic film, the reflected field will create the second $\Delta\vec{H}$ at $t = t_1$. The observed rate of flux change from such an experiment is shown in Fig. 8. This trace may be contrasted with the typical single step oscillatory behavior as shown in Fig. 5. Fig. 8 shows the almost complete disappearance of oscillation when the double-step pulse is used. The negative pulse in Fig. 8 corresponds to the two-step removal of the field in the stripline. \vec{M} swings back to its original position.

For a larger amount of damping, the spiral will be more pronounced and the direction of \vec{M} will fall noticeably short of $\vec{H}_0 + 2\Delta\vec{H}$. Since

\vec{M} and \vec{H} will not be perfectly aligned, there will be residual ringing in the output due to precession of \vec{M} about $\vec{H}_0 + 2\Delta\vec{H}$. If an appropriate amount of loss is added to the transmission line, the second step will be reduced so that \vec{M} and \vec{H} will align at $t = t_1$. This match of transmission line loss to precession damping would be especially important in the case where the switching pulse rate is a subharmonic of the resonance frequency and any residual ringing could add in phase.

Other variations of this step technique have been suggested. For example, if it is required that the step field $\Delta\vec{H}$ and the switched state $\vec{M}_{t=t_1}$ be orthogonal to the initial magnetization, then a version of the arrangement shown in Fig. 9 might be useful. A pulse $\Delta\vec{H}$ which is orthogonal to and equal in magnitude to \vec{H}_0 is applied at $t = t_0$. At $t = t_1$, \vec{M} is at right angles to the initial direction (neglecting damping). However, \vec{M} cannot be stopped at $t = t_1$ by adding another $\Delta\vec{H}$ in the same direction as the first, so \vec{M} is permitted to swing back to the original position. At $t = 2t_1$, $\Delta\vec{H}$ is applied opposite to the original step (i.e., the pulse field is removed), and \vec{M} comes to rest in the original position. With this configuration \vec{M} remains in the switched state momentarily, whereas in Figs. 4 and 5 \vec{M} could be held in the switched state.

CONCLUSIONS

It has been demonstrated that the alternate sampling technique using a lock-in amplifier for added sensitivity can be used to observe the precession behavior of the magnetization in ferrimagnetic films. A very

underdamped precession has been observed in a $(Y_{2.5}Gd_{.5})(Fe_4Ga_1)O_{12}$ thin film on GGG. Further, a "quelled-precession" technique has been demonstrated which takes advantage of the low damping to obtain nanosecond switching speeds between different magnetization directions.

ACKNOWLEDGEMENTS

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FINANCIAL STATEMENT

Contract N00014-73-C-0256

Total Amount Contract

\$99,000

Inception to Date

\$99,000

Unexpended Funds

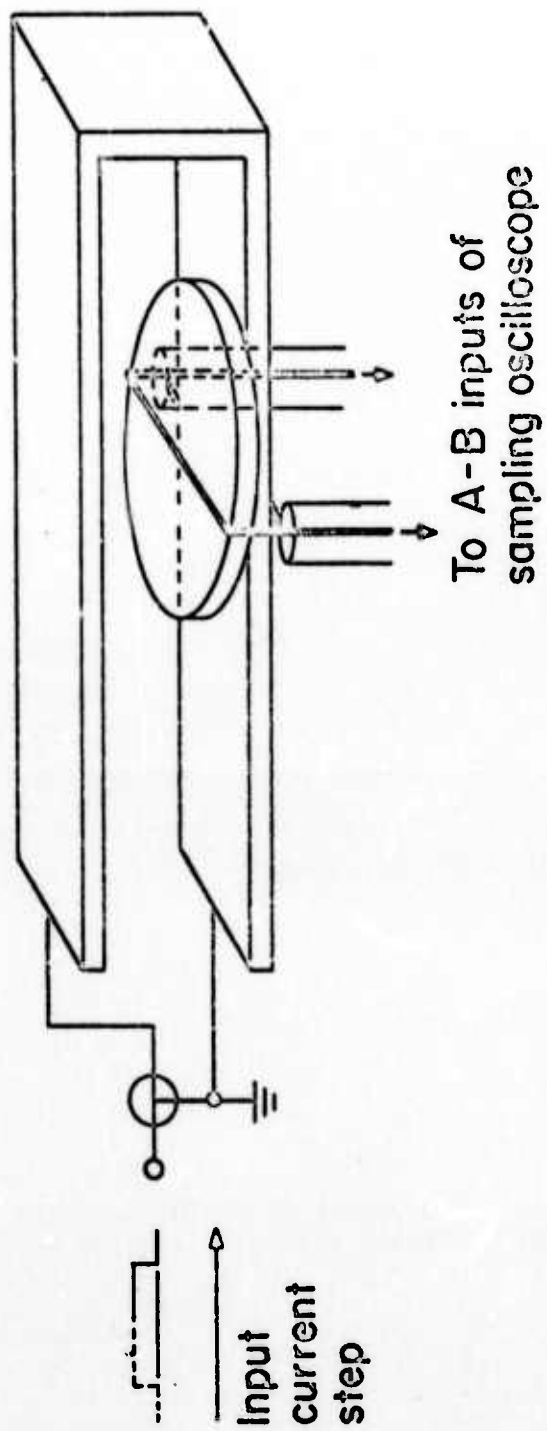
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Required Level of Effort

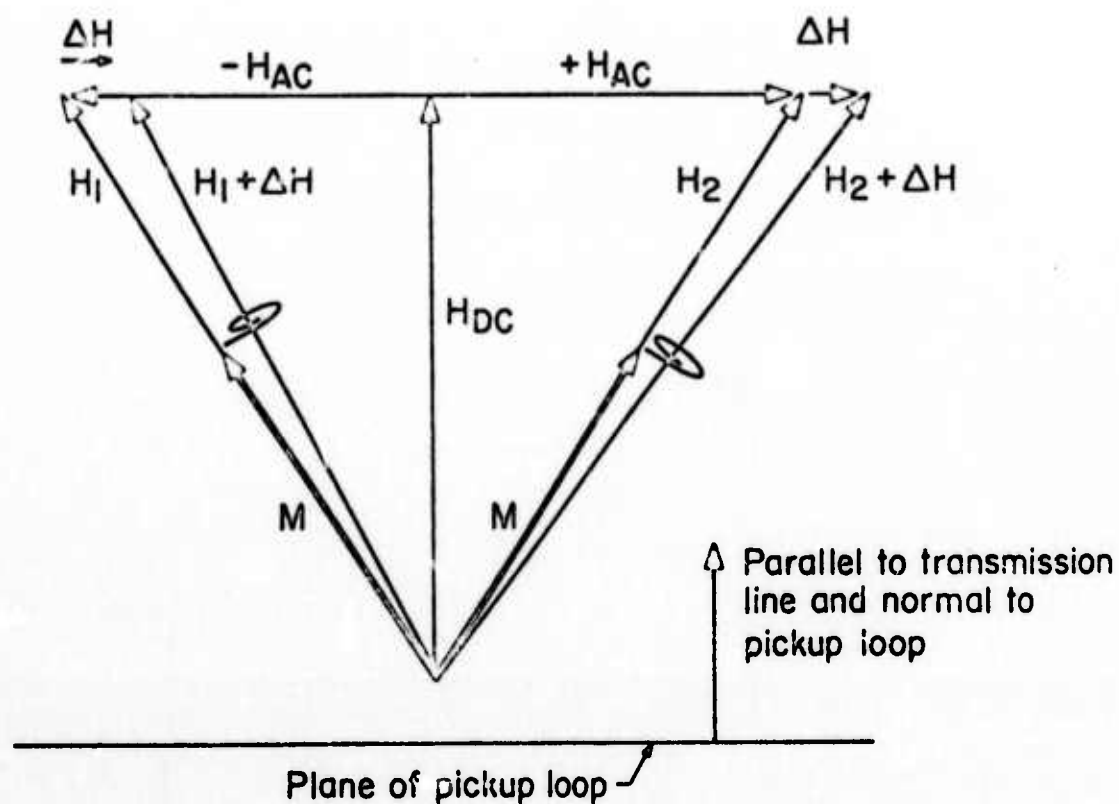
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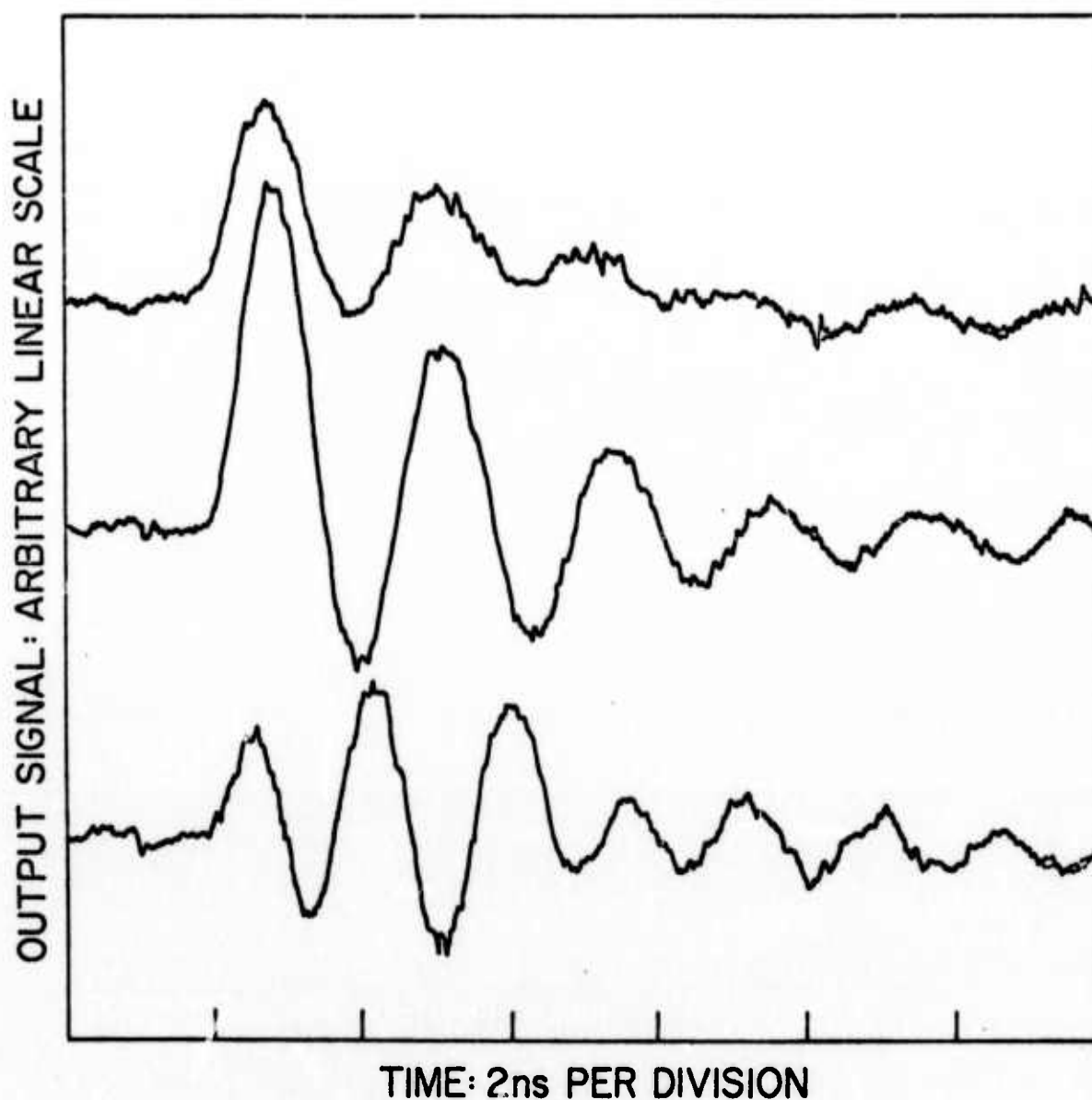
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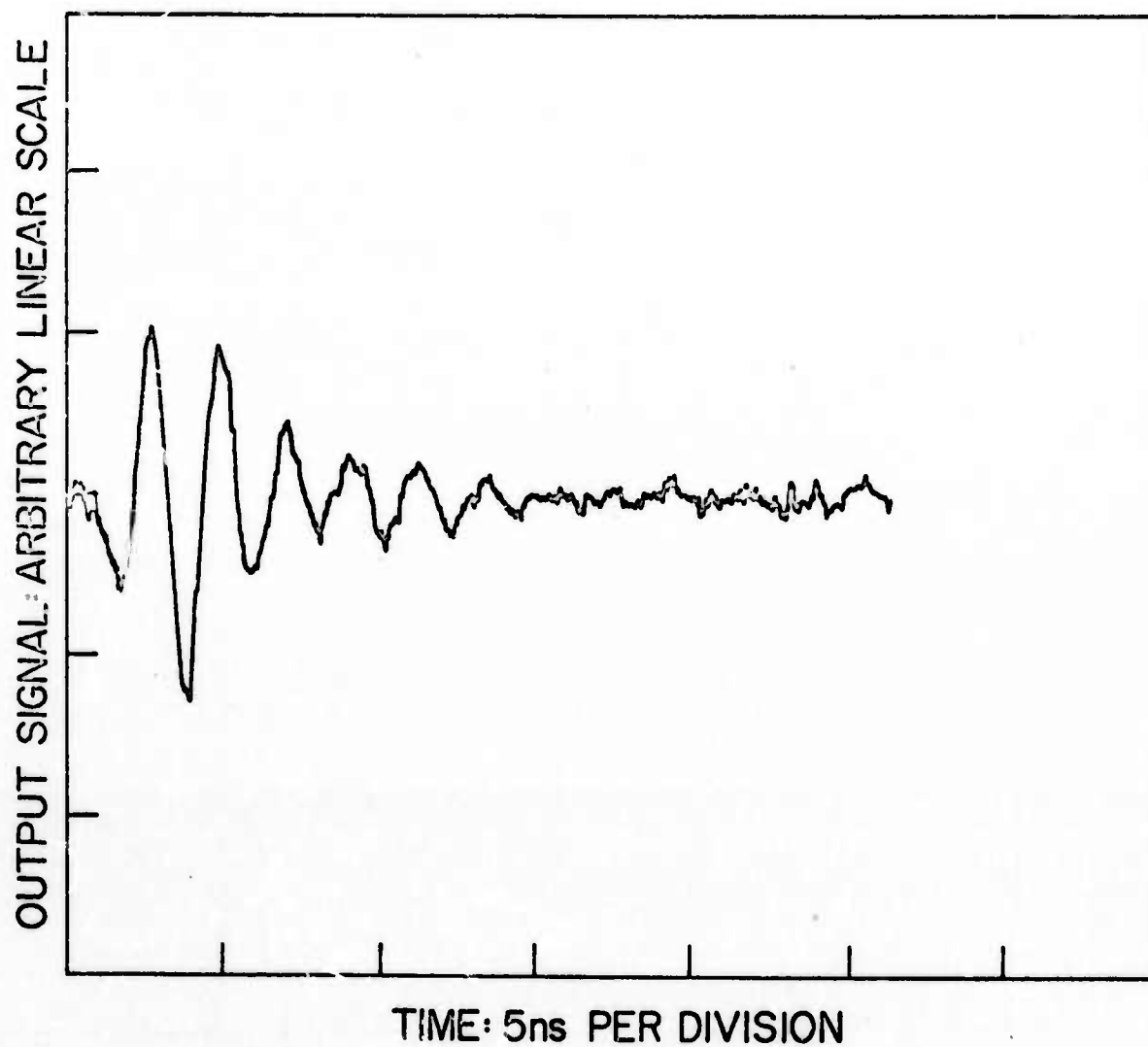
- 1) Sketch of strip transmission line showing sample placed inside pickup loop.



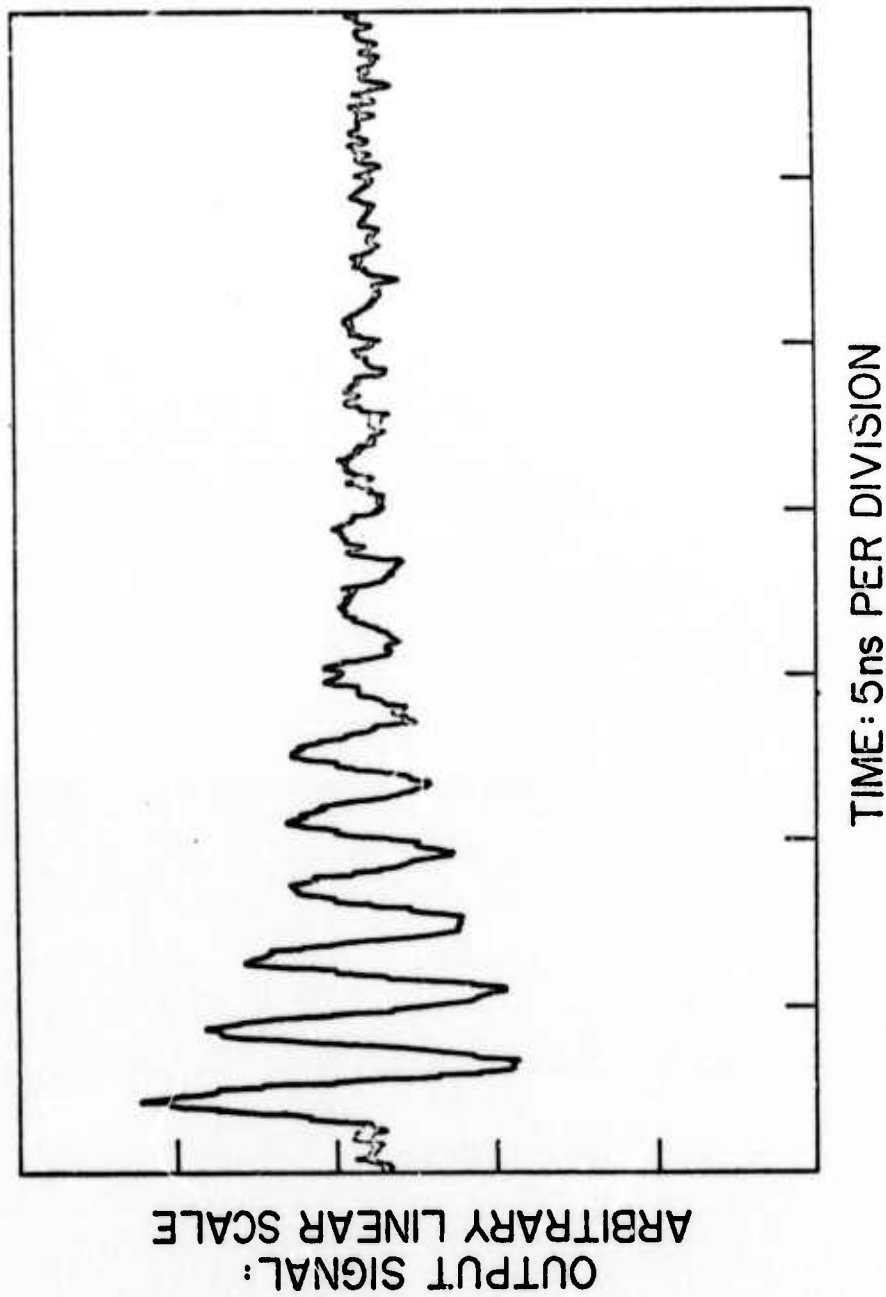
- 2) With this symmetrical arrangement of fields, the two flux responses due to precession of M about $H_1 + \Delta H$ and $H_2 + \Delta H$ may be combined constructively.



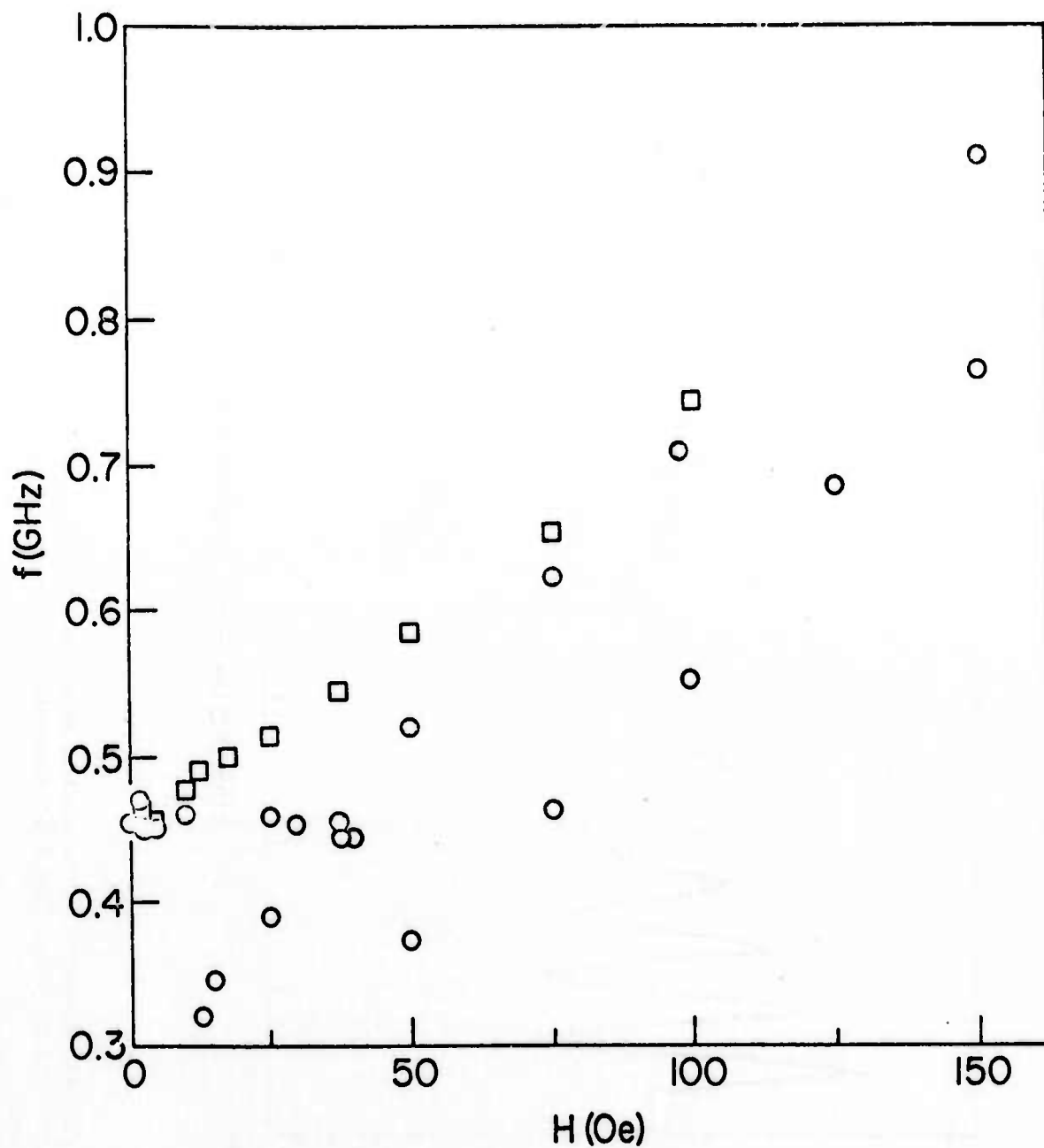
- 3) Changes in output for different sample orientations. The upper, middle and lower traces were made with the easy axis rotated away from the direction of H_{AC} and ΔH by an estimated 30, 10, -10 degrees respectively. H_{DC} was perpendicular to H_{AC} and ΔH as shown in Fig. 2.



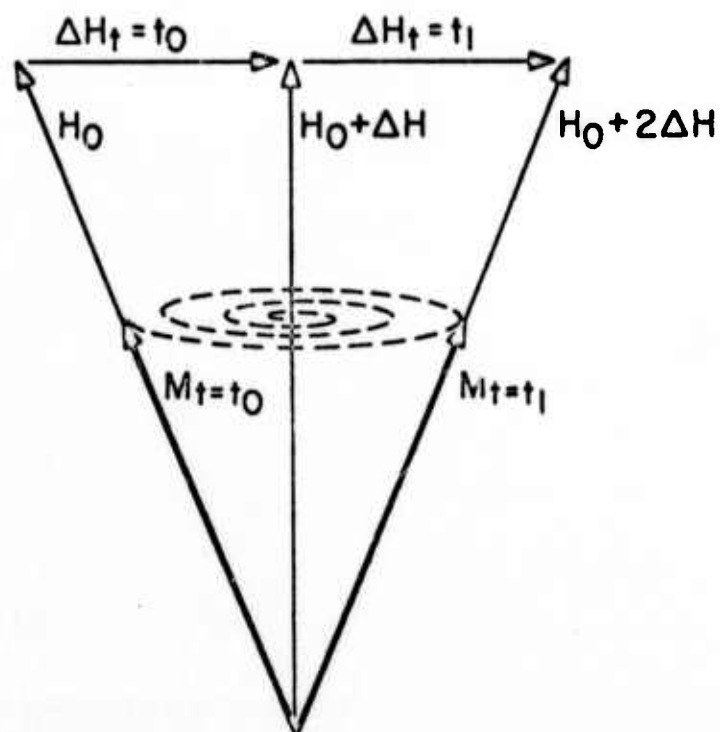
- 4) Output from the difference in precession about external fields of 50 and -20 Oe perpendicular to the easy axis.



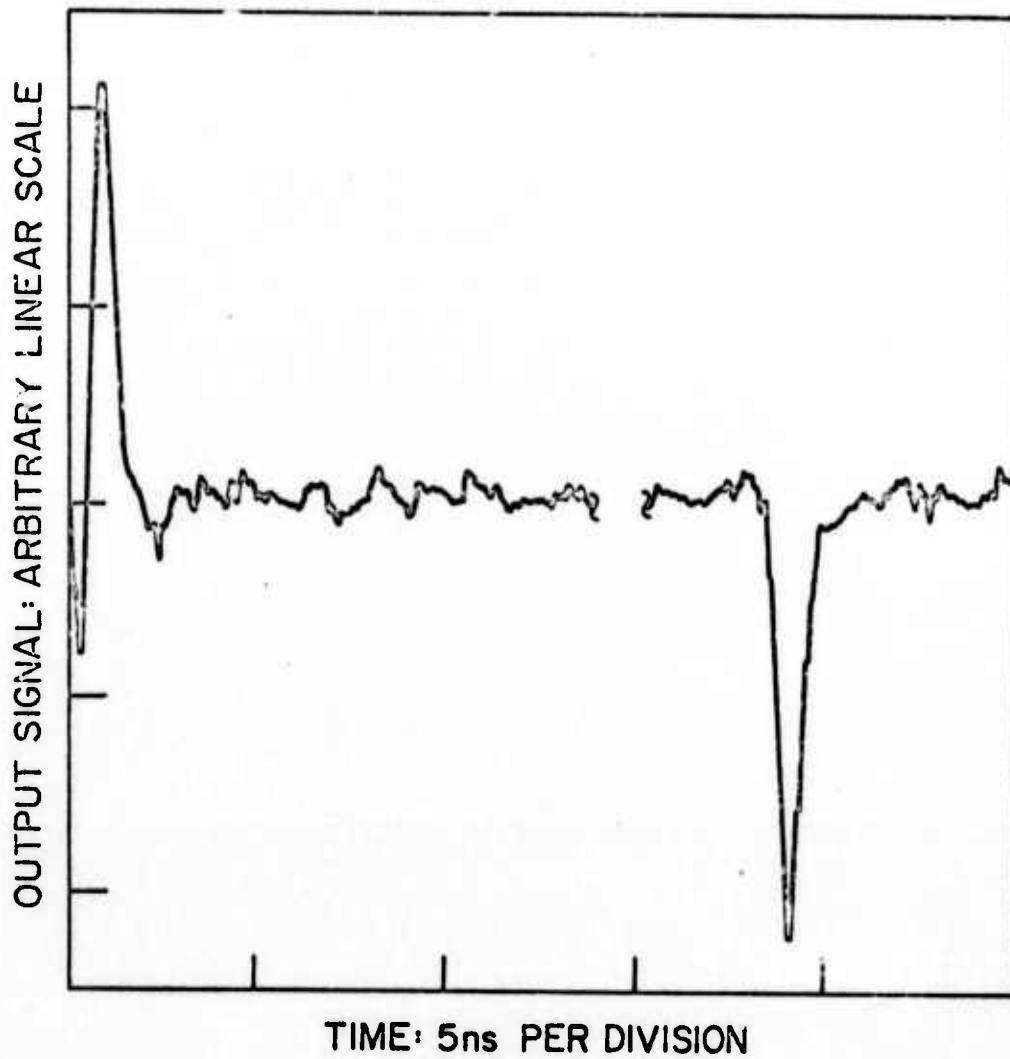
- 5) Output from the difference in precession about 40 Oe external fields.
Sampling alternated between field orientation ± 45 degrees with respect to the easy axis.



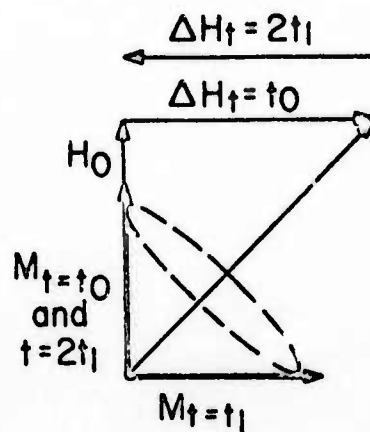
- 6) Frequency f of transient responses versus amplitude of external field H . The easy axis was perpendicular to H for the closed circles, parallel to H for the open circles, and at 45 degrees to H for the square points.



- 7) Quelled precession permits switching in a half cycle of the precession frequency. One step ΔH initiates the precession; a second ΔH , appropriately timed, stops the precession and prevents the continuation of the spiral.



- 8) Response using quelled precession technique. The initial double step initiates, then quells, the precession in such a way that the magnetization is switched in one direction. A later double step of the opposite polarity switches the magnetization back to the original state.



- 9) Right angle switching. After ΔH is applied at $t=t_0$, M precesses through $M_{t=t_1}$ back to the initial direction at $t=2t_1$. Then H is changed back to H_0 and precession stops. Effective internal fields must be considered as part of H_0 .